AERIAL BASE STATION DEPLOYMENT IN 6G CELLULAR NETWORKS USING TETHERED DRONES

The Mobility and Endurance Tradeoff

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Airborne base stations (BSs) (carried by drones) have a great potential to enhance the coverage and capacity of 6G cellular networks. However, one of the main challenges facing the deployment of airborne BSs is the limited available energy at the drone, which curtails the flight time. In fact, most current unmanned aerial vehicles (UAVs) can only operate for a maximum of 1 h. The need to frequently visit the ground station (GS) to recharge limits the performance of the UAV-enabled cellular network and leaves the UAV's coverage area temporarily out of service. In this article, we propose a UAV-enabled cellular network setup based on tethered UAVs (tUAVs). In the proposed setup, the tUAV is connected to a GS through a tether, which provides the tUAV with both energy and data. This enables a flight that can last for days. We describe in detail the components of the proposed system. Furthermore, we list the main advantages of a tUAV-enabled cellular network compared to typical untethered UAVs (uUAVs). Next, we discuss the potential applications and use cases for tUAVs. We also provide Monte Carlo simulations to compare the performance of tUAVs and uUAVs in terms of coverage probability. For instance, for a uUAV that is available 70% of the time (while unavailable because of charging or changing the battery 30% of

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THE GS LOCATION SELECTION PROCESS SHOULD TAKE MULTIPLE ASPECTS INTO CONSIDERATION, SUCH AS THE TRAFFIC DEMAND SPATIAL DISTRIBUTION AND THE AVAILABILITY OF THE REQUIRED INFRASTRUCTURE.

the time), the simulation results show that tUAVs with a 120-m tether length can provide up to a 30% increase in coverage probability compared to uUAVs. Finally, we discuss the challenges, design considerations, and future research directions to realize the proposed setup.

Overview

Drone-carried BSs are believed to be an integral part of the 6G cellular architecture [1], [2]. The inherent relocation flexibility and relative ease of deployment can be beneficial for multiple requirements of next-generation cellular networks, such as providing coverage in hotspots and in areas with scarce infrastructure, including disaster-recovering environments or rural areas. The higher probability of establishing a line-of-sight (LoS) link with ground users because of the high altitude leads to more reliable communication links and wider coverage areas [3], [4]. Potential use cases for airborne BSs include 1) offloading macro BSs (MBSs) in urban and dense urban areas and 2) providing coverage for rural areas, which typically suffer from low cellular coverage due to a lack of incentives for operators.

These potential advantages of airborne BSs have motivated the research community to study multiple aspects of UAV-enabled cellular networks, such as the air-to-ground (A2G) channel characteristics, optimal placement of UAVs, and trajectory optimization [5]. In addition, this article discusses two key design challenges for UAV-enabled systems in more detail. The first is the limited energy resources available onboard, which limits the flight time to less than one hour in most commercially available UAVs [6], [7]. The second challenge is the wireless backhaul link [8].

Typically, the energy consumption of a UAV is twofold: 1) propulsion energy, which is the energy consumed by the UAV for the purpose of flying and hovering, and 2) payload energy, which captures the energy consumption for communication and on-board processing. Many research works have been directed to designing energy-efficient communication schemes to prolong UAVs' lifetimes. However, since the propulsion energy is significantly more than the payload energy, energy-efficient communication will not highly affect the flight time. Such short flight times might not be an issue for some use cases, such as drone-based delivery between nearby locations or data dissemination and collection from sensor networks. However, when it comes to establishing a UAV-mounted BS, longer flight times are vital to ensure stable and uninterrupted cellular service.

Unlike terrestrial BSs, which have wired backhaul links (typically using fiber cables), uUAVs rely on wireless backhaul links. Compared to wired links, wireless backhaul links are susceptible to higher latency, interference, and lower achievable data rates. Hence, it is important to find the best technology to establish a wireless backhaul link at the uUAV [8]. Available solutions in the literature include 1) satellite communication, 2) millimeter-wave (mm-wave) communication, 3) free-space optical (FSO) communication, and 4) in-band backhaul communication. Each solution has specific pros and cons. For instance, satellite communication ensures a more reliable backhaul link but suffers from higher latency. On the other hand, mm-wave and FSO backhaul links ensure much higher data rates than in-band backhaul. However, both solutions suffer from high vulnerability to blockage and are reliable only over short distances. Using in-band backhaul receives the most attention in current literature. This solution has lower latency than satellite backhaul. It does not require an LoS channel to communicate efficiently, like mm-wave or FSO. However, due to the high altitude of the uUAV, it suffers from higher levels of interference, which can reduce the achievable rate of the backhaul link significantly.

In this article, we propose a system setup based on tUAVs. The proposed technology solves the two technical challenges previously discussed: 1) short flight time due to limited onboard energy and 2) establishing a reliable backhaul link. The interface between the GS and the tUAV is twofold: energy supply and data link. The energy supply is provided by the GS to the tUAV through a wired connection, which enables the tUAV to sustain much longer flight times. Similarly, the data link between the GS and the tUAV is also physical through a fiber link, which ensures reliable communication at high data rates between the tUAV and the GS. Both wired connections for energy and data are aggregated in the tether. Currently, commercially available tUAVs can stay in the air and operate without interruption for days and have proven their capability to tolerate harsh weather conditions. Due to its weight, the tether length is typically limited and ranges between 80 and 150 m [9]. A recent incident in Puerto Rico saw the deployment of a tUAV to provide cellular coverage for affected regions after Hurricane Maria [10].

The main drawback of tUAVs is the limited tether length, which restricts the mobility and relocation flexibility of the drone. Hence, a tradeoff naturally comes into the picture between uUAV and tUAV. On one hand, the tUAV has a much longer flight time than the uUAV due to the stable power supply through the tether. However, it can hover or relocate only within a restricted space defined by the tether length and the GS's surroundings. On the other hand, the uUAV has complete freedom to hover and relocate anywhere to maximize network performance. However, due to the limited on-board battery, it has to interrupt its operation regularly to recharge or replace its battery. Unfortunately, today we do not have technology that can ensure long flight times while maintaining free mobility (tetherless). In Figure 1, we visualize the key differences between terrestrial BSs, uUAVs, and tUAVs in terms of main system advantages. It can be observed that the tUAV sacrifices the mobility and relocation flexibility of uUAVs to maintain the main requirements of a reliable cellular BS in terms of endurance and backhaul link quality. In this article, we describe in detail the tUAV system, discuss the main advantages of tUAVs and their potential applications and use cases, and list the main challenges and design considerations that need to be carefully studied in future research work.

System Setup

As shown in Figure 2, the proposed system setup consists of three main components:

- the tUAV
- the tether
- the GS.

The GS is placed at a carefully selected location that satisfies two conditions: 1) it has a reliable connection to the core network, and 2) it has a stable resource of energy, such as the grid or a generator. These two connections (energy resource and core network) are extended to the tUAV through the tether. Hence, the tether provides the tUAV with an uninterrupted energy supply, enabling it to stay in operation for significantly extended flight times. In addition, the tether also connects the tUAV to the core network through a wired connection, providing it with a stable, reliable, and secure backhaul link.

The tUAV can hover only within a specific range, which mainly depends on the tether length. Assuming the GS, which is the launching point of the tUAV, is placed on a rooftop, the tUAV can hover around the rooftop within a truncated hemisphere of radius equivalent to the tether length and centered at the rooftop, as depicted in Figure 3. The overall region within which the tUAV can hover is limited by the heights of the neighboring buildings. Motion planning techniques can be adopted to determine the reachable 3D locations for a given environment, as discussed in [11]. In the rest of this article, we will refer to this region as the *hovering region*.

The tUAV carries the antennas and a set of processing units. These processing units are connected to the GS through a data-carrying optical fiber along the tether. While the antennas and processing units are considered heavy components for typical UAVs, current commercially available tUAV systems can carry up to 60 kg of additional payload [12]. The tUAV should hover within the hovering region and find the optimal 3D location that maximizes the cellular coverage for ground users.

Beside its main job of providing the connection to the core network and energy resource, the GS is responsible for controlling the tether. In particular, the GS should control the tension of the tether and ensure that it is taut at all times. During the tUAV's motion, the GS should sense whether the tUAV requires releasing more length to reach its intended destination or retracting extra length to ensure a taut tether [13], [14].

It is clear from this discussion that the smart selection of the GS's location is of high importance for the

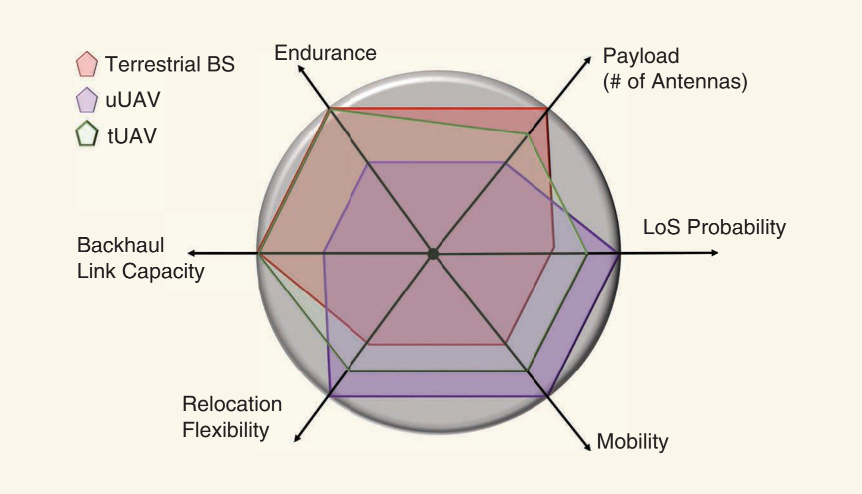

FIGURE 1 A comparison among terrestrial BSs, uUAVs, and tUAVs.

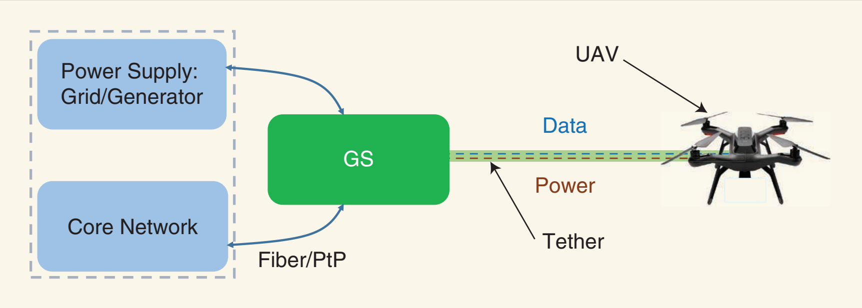

FIGURE 2 A block diagram of the considered tUAV system setup. PtP: point to point.

ONE MORE ADVANTAGE FOR THE tUAV OVER THE TERRESTRIAL BS IS THE REDUCED TERRESTRIAL FOOTPRINT.

performance of the tUAV system. For instance, placing the GS on a rooftop surrounded by taller buildings on all sides would reduce its hovering region to mainly the area above its own rooftop. A smaller hovering region leads to a more constrained tUAV 3D placement problem and limits the mobility of the tUAV. The GS location selection process should take multiple aspects into consideration, such as the traffic demand spatial distribution and the availability of the required infrastructure.

Aside from performance, the design of the tUAV's system should take cost efficiency into consideration. Some differences exist between a tUAV and uUAV in terms of capital expenditure (CAPEX) and operational expenditure (OPEX). The CAPEX that exists only in tUAV systems results mainly from 1) the tether and its mechanical controller and 2) the GS. Meanwhile, the CAPEX that exists only in uUAV systems results mainly from the charging stations required to recharge/replace the batteries of the uUAV. On the other hand, the OPEX that exists only in tUAV systems mainly results from the rental of the rooftops that are used to deploy the GS.

Main Advantages

As discussed previously, uUAVs are limited by the onboard battery as the sole resource of energy. Given that it typically takes less than 1 h for battery depletion, the uUAV operation itself is quite limited in many aspects. For instance, the payload of the uUAV is typically kept low to reduce energy consumption during operation, the power dedicated to communication with GSs or ground users is limited, and the relocation of the uUAV should be minimized, since it consumes most of the available energy onboard. Hence, the uUAV's energy limitations significantly affect its performance and reliability as a stable aerial BS. In this section, we discuss in more detail the advantages of tUAVs over uUAVs or terrestrial BSs.

Advantage 1: The tUAV can stay in operation for days. It needs to land at the GS only for maintenance, which is a normal procedure even for terrestrial BSs. Prolonged flight times of the tUAVs make them comparable to terrestrial BSs in terms of endurance. However, tUAVs have the advantage of higher altitude and more mobility (within the hovering range), which can be exploited to optimally place and relocate the tUAV according to traffic demands and channel conditions with mobile users. Furthermore, compared to terrestrial BSs, a tUAV has a much safer maintenance procedure, since it does not require climbing high towers. One more advantage for the tUAV over the terrestrial

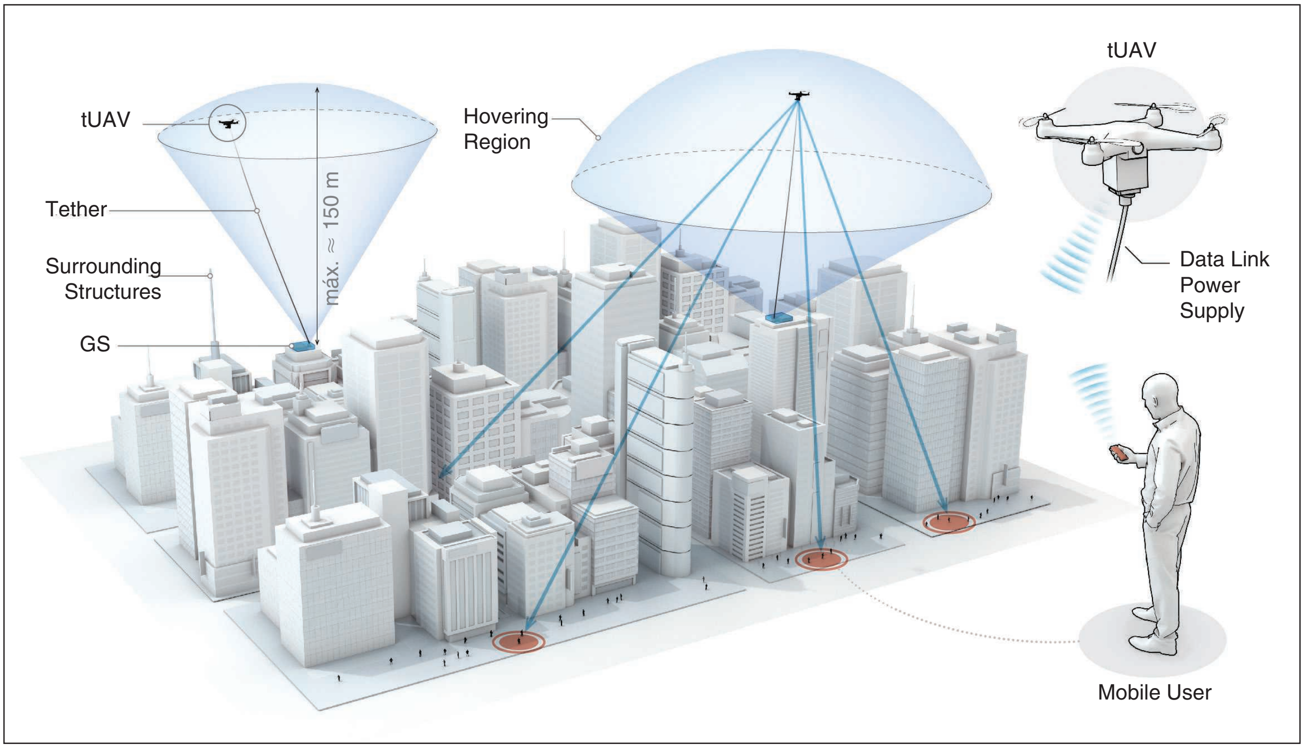

FIGURE 3 tUAVs in urban areas. (Source: Xavier Pita; used with permission.)

BS is the reduced terrestrial footprint. The space required for the GS can be as small as the rooftop of a typical urban building. This space is only required to place some processing units and establish the connections to the energy resource and the core network. In addition, unlike the deployment of terrestrial BSs, which are fixed and permanent, the GS of the tUAV (which is its launching point) can be relocated whenever necessary from one rooftop to another.

Advantage 2: The tUAV can sustain heavier payloads than uUAVs. This is due to the existence of a stable energy resource connected to the tUAV through the tether. In fact, current commercially available tUAV products can achieve up to 60 kg of payload [12]. Thus, tUAVs can afford having more antennas and radio chains, which enables sectorization and/or multiple antenna communications. Thus, tUAVs offer more capacity and better interference management than uUAVs.

Advantage 3: Due to having a wired data link with the GS through the tether, tUAVs can delegate some of the processing units to the GS, such as the baseband unit. This reduces the used tUAV payload, which enables placing more antennas on the tUAV.

Advantage 4: As explained previously, one of the main research challenges in establishing uUAV as an aerial BS is backhaul communication. In fact, there is a tradeoff between placing the uUAV close to the terrestrial BS to ensure a strong and reliable backhaul link with high capacity and placing the uUAV close to the mobile users to enhance the quality of the channel between the uUAV and users. Hence, even in the uUAV, free mobility and flexible placement are still constrained by the quality of the backhaul link and the distance to the terrestrial BS, which can be considered a virtual tether. On the other hand, a tUAV has a stable wired connection to the GS with significantly higher capacity than a wireless backhaul link. Not only does this affect the achievable data rates due to the high backhaul capacity; it also frees more resource blocks for serving mobile users reserved for the wireless backhaul link in uUAV systems.

Advantage 5: One of the major concerns when using a uUAV is drone flyaway. During uUAV operation, flyaway can result for many reasons, such as software glitches, lost connection between the GS and uUAV due to the uUAV flying out of control range, hardware failure, interference in the communication channel leading to loss of control, or strong wind. In addition to the financial loss and negative effect on the performance of the uUAV-enabled communication system, a drone flyaway imposes numerous public risks. The drone may crash into a pedestrian, a building, or a highway, possibly causing dangerous accidents. Many accidents resulting from drone crashes or flying in improper areas were reported over the past few years, such as the incident at Gatwick Airport, when the airport had to suspend flights in and out for several hours due to the sight of two drones near the runway. While uUAVs are susceptible to all such risks, tUAVs are physically connected to the GS through the tether. This limited-length tether can add another measure of controllability to the tUAV and prevent the drone from straying away. In fact, the tether is used in some works specifically to enhance the safety of the tUAV and its resistance to wind and harsh weather conditions. The tether can also be used as an alternative to GPS to determine the location of the tUAV and ensure a safer landing.

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Use Cases

The typical use cases for uUAV-mounted BSs are limited to temporary scenarios, such as providing coverage for disaster areas with temporarily unavailable infrastructure or events like concerts or soccer games. However, given their longer flight times, tUAVs can provide cellular coverage for many more scenarios. They maintain the reliability of terrestrial BSs, in terms of providing uninterrupted service, while bringing the inherent advantages of deployment at high altitude.

Use Case 1: Capacity Enhancement and Traffic Offloading in Dense Urban Areas

tUAVs' main applications and use cases are those that require high endurance and prolonged flight time. For instance, a uUAV with a flight time of one hour is eligible for applications like providing cellular coverage in emergency scenarios or short-term events. However, traffic offloading in urban areas requires more sustainable UAV operation, which is a perfect fit for the tUAV capabilities. As demonstrated in Figure 3, GSs can be placed on multiple rooftops in dense urban areas. As noted previously, the taller the rooftop, the larger the hovering region of the tUAV gets. Having multiple tUAVs with large hovering regions enables changing the constellation of the tUAVs in the sky whenever needed, based on the traffic demands and the user locations. Reaching such flexibility in the spatial distribution of the tUAVs actually reduces the effect of the mobility restrictions induced by the tether, leading to a performance almost similar to that of uUAVs in terms of mobility and relocation flexibility.

Use Case 2: Coverage Enhancement in Rural Areas

Network operators are often not willing to invest in rural and low-income areas, due to the high costs of network deployment and low potential profits. As briefly

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discussed previously, tUAVs require much less time and money for deployment and operation than typical terrestrial BSs. As exhibited in Figure 4, a tUAV communication system can be used to enhance cellular coverage in rural areas. Due to the nature of rural areas, where there are not many tall buildings, placing the GS on a moving vehicle can be enough to achieve large hovering regions. In addition, since rural traffic demands are significantly lower than those of their urban counterparts, continuously changing the spatial location of the tUAV will not be necessary.

Use Case 3: Network Densification

One of the top benefits of airborne BSs is the quality of the A2G channel with mobile users. Due to the higher probability of establishing an LoS A2G channel, the coverage radius of an airborne BS is higher than that of a terrestrial BS. With the stable power supply carried through the tether enabling long-term operation, tUAVs can be used for network densification in areas with high traffic demand. Even though tUAVs' mobility is restricted compared to that of uUAVs, it still brings the benefits of high-altitude deployment.

Endurance Versus Mobility: Simulations and Discussion

In this section, we aim to show, with the aid of Monte Carlo simulations, the tradeoff between tUAVs and uUAVs in terms of unconstrained mobility with limited flight time for uUAVs and constrained mobility with unlimited flight time for tUAVs. We first consider a system setup composed of an MBS, a cluster of users, and a UAV deployed to serve this cluster of users and offload the MBS. The locations of the users are uniformly distributed inside a cluster with a radius of 100 m. In the case of using a uUAV, we assume that the uUAV hovers at the center of the cluster to maximize coverage. However, due to battery limitations, the uUAV has to leave its aerial location and fly back to a charging station to recharge/replace its battery. During this time, users are served only by the MBS. Hence, we introduce the uUAV's availability as the fraction of the time when it is actually operating. On the other hand, in the case of using a tUAV, we assume that it has unlimited flight time. However, its mobility is limited by a tether with a length of 120 m connecting it to the MBS, similar to the tUAV specifications described in [15]. Hence, here we are assuming that the tUAV's GS is the MBS. In Figures 5 and 6, we observe that, in the case of having a uUAV with availability of 1, we will have the best possible coverage. However, as discussed previously, we do not yet have the technology to achieve such a setup. In the case of having an availability of 0.8, the tUAV outperforms the uUAV as long as the distance

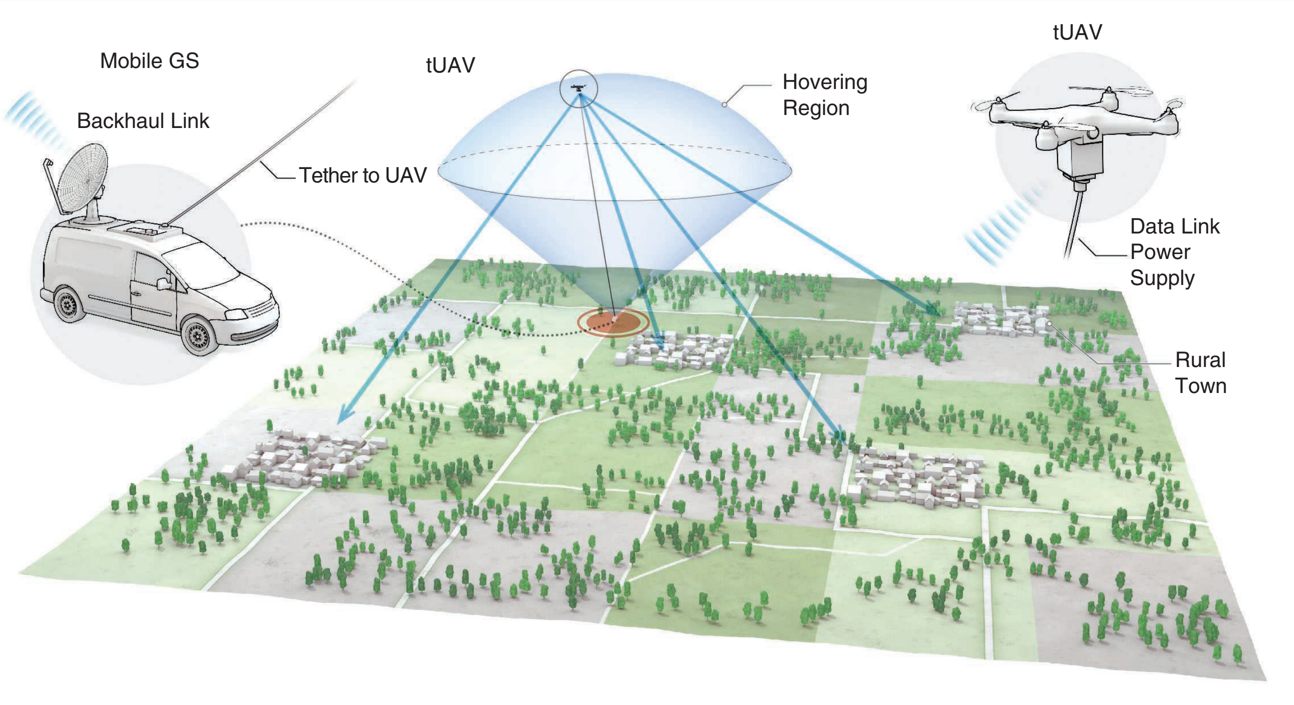

FIGURE 4 tUAVs in rural areas. (Source: Xavier Pita; used with permission.)

between the MBS and the cluster center is below 193 m. This threshold increases when the availability of the uUAV decreases.

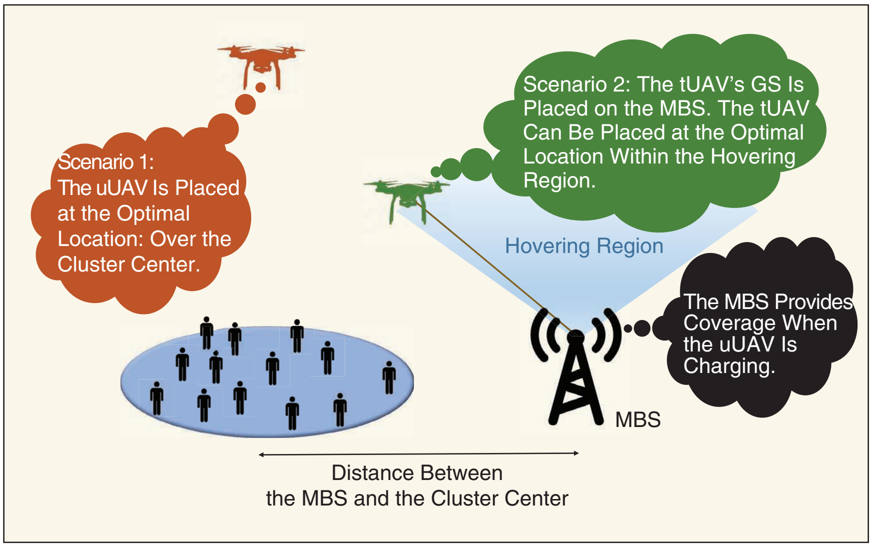

FIGURE 5 The system setup for Figure 6.

In Figure 6, we also compare the performance of the tUAV for two deployment scenarios: 1) the tUAV is hovering exactly above the GS with the tether extended to its maximum value and 2) the tUAV is placed at the optimal location within its hovering region that maximizes the coverage probability. The results show the importance of the tUAV's optimal placement. Note that the placement optimization problem of the tUAV is different from the typical 3D placement problems of uUAVs discussed in the literature. This is mainly due to the restricted mobility of the tUAV, which reduces its reachable 3D locations. Note that this placement problem is different from the scenario of having a maximum allowable altitude for the uUAV. For the latter, the uUAV can hover anywhere as long as it maintains its altitude below a given value, which is not the case for the tUAV. For more details, refer to [9].

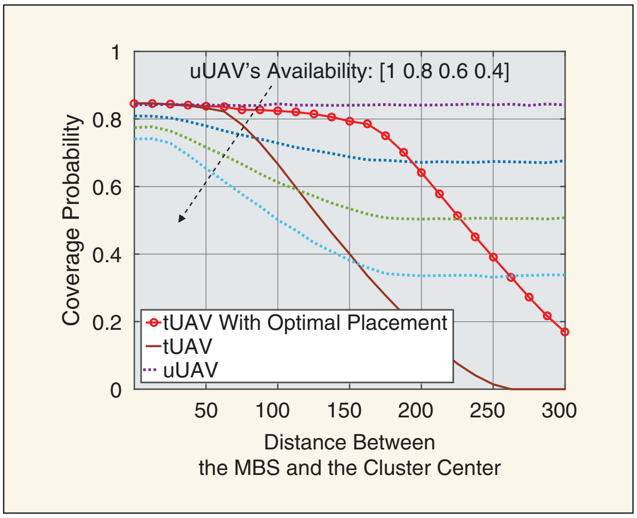

FIGURE 6 The coverage probability when using either the tUAV or uUAV for different values of the distance between the MBS and the cluster center. In this simulation, as depicted in Figure 5, we consider a setup of one circular cluster of users, with the users uniformly distributed inside a disk with a radius of 100 m. The uUAV's availability defines the fraction of time during which the uUAV is operating, where the rest of the time it is recharging/swapping its battery. The tUAV is connected to an MBS through a tether with a length of 120 m [15]. We compare three scenarios: scenario 1 is when the uUAV is used and the main limitation is its availability, scenario 2 is when the tUAV is used and placed at the optimal location within the hovering region, and scenario 3 is when the tUAV is placed directly above its GS (no optimal placement is considered).

As stated previously, the GS does not have to be an MBS. It can be the rooftop of any building as long as it has access to a stable energy resource and a reliable connection to the core network. Obviously, these conditions are not always satisfied by any randomly selected building. In addition, not every building satisfying these conditions will grant access to the operator to deploy its GS on its rooftop. Hence, for a given density of buildings, we introduce rooftop accessibility as the ratio of buildings that satisfy the aforementioned conditions and are willing to grant access to their rooftops. We consider a setup similar to that in Figure 6, with the GS deployed at the nearest accessible rooftop to the cluster center instead of deploying it at the MBS. In addition, we fix the distance between the MBS and the cluster center to 160 m. We model the locations of the buildings using a Poisson point process with a density of 500 buildings/km^2, which is the typical density of buildings in urban areas. In Figures 7 and 8, we compare the performance of a uUAV and tUAV for different values of rooftop accessibility. We observe that the minimum required rooftop accessibility for the tUAV to outperform the uUAV decreases as we increase the tether length. For instance, when the availability is 0.9, the required rooftop accessibility decreases from 0.25 to 0.05 as we increase the maximum tether length from 80 to 120 m. This result shows the influence of the maximum tether length on system performance. Given that the rooftop accessibility constitutes an important part of the CAPEX of the system, these results show that increasing the maximum tether length is actually important for cost-efficient deployment of tUAVs.

Challenges and Design Considerations

The challenges of uUAV communications have received extensive discussion in the literature, especially issues arising from deployment at such high altitude. Hence, in

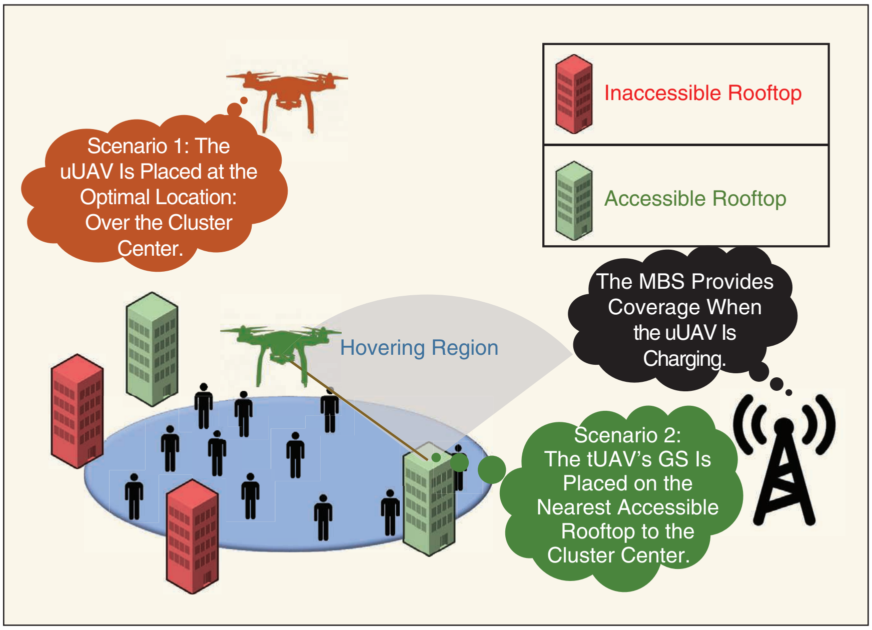

FIGURE 7 The system setup for Figure 8.

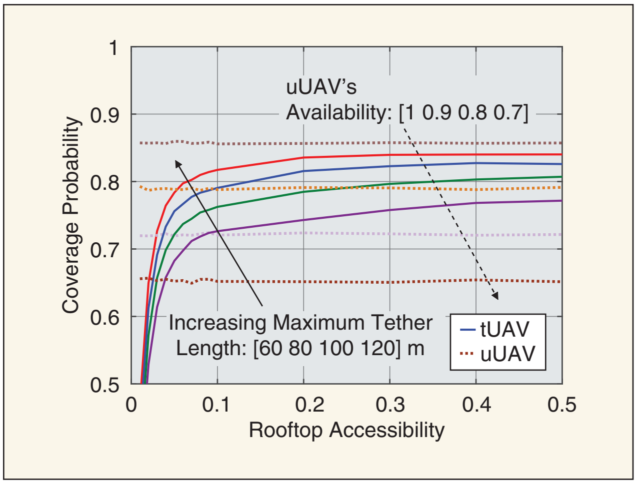

FIGURE 8 The coverage probability for different values of uUAV's availability, maximum tether length, and rooftop accessibility. In this simulation, as presented in Figure 7, we study the coverage of uniformly distributed users within a disk of radius 100 m. The MBS is located 160 m away from the disk center. The GS of the tUAV is placed on the nearest accessible rooftop to the disk center. Rooftop accessibility defines the fraction of the buildings where the deployment of the GS is permitted. The density of the buildings is 500 buildings/km^2. We compare 2 scenarios: (i) scenario 1 is when uUAV is used and the main limitation is its availability, and (ii) scenario 2 is when tUAV is used and the GS is placed at the closest accessible rooftop to the cluster center.

this section, we focus on challenges related specifically to the proposed setup. In particular, we include the challenges that exist only in tUAV setups but not in uUAV ones.

Challenge 1: While airborne communication systems, in general, require new regulatory policies, tUAV systems might need some special considerations. For instance, new safety regulations should be implemented for the areas where tethers are allowed to extend. Safety margins around buildings and aboveground have to be kept to avoid any accidents because of tangling or any malicious attempts to mess with the tether. Given the high importance of the tether in the system, carrying data and providing power to the drone, its safety is vital to the safety of the drone. These restrictions impose some constraints on potential deployment locations for the GS and the hovering regions. Hence, the tUAV optimal placement problem should take such safety regulations into consideration.

Challenge 2: As can be noticed from Figure 3, it makes more sense to place the GSs on tall rooftops when establishing tUAV systems in dense urban areas due to the high density of obstructions (tall buildings). On the other hand, as observed from Figure 4, rural areas are less obstructed; hence, the altitude of the tUAV does not have to be very high, making it sufficient to place the GS on a moving vehicle. However, when deploying tUAV systems in urban or suburban areas, a tradeoff comes into the picture. On the one hand, placing the GS on a moving vehicle has the advantage of mobility and, hence, the ability to relocate the GS, whenever needed, toward areas with more user density and higher traffic demand. In addition, it is less expensive than rooftops, which require monthly/annual rents for building owners. On the other hand, rooftops have the advantage of higher altitude, which adds an extra hovering region for the tUAV given the limited tether length. In addition, it keeps the tether away from public access, ensuring safer operation.

Challenge 3: The tUAV placement problem is unlike typical uUAV placement optimization research work. Each tUAV has to be physically connected to the GS on the rooftop through the tether during operation. Hence, the problem is more constrained and needs to be carefully studied. The rooftop selection problem can be solved using different approaches depending on the main objectives of the operator in terms of quality of service. In addition to cellular-coverage-related considerations, cost efficiency should also be taken into account during the rooftop selection process. In fact, there is a tradeoff between deploying fewer tUAVs on tall rooftops located in the middle of user hotspots (probably higher rents) and deploying more tUAVs on shorter rooftops. This tradeoff between CAPEX (number of tUAVs) and OPEX (rooftop rents) adds another layer of complexity to the optimal rooftop selection problem.

Challenge 4: Given the location selected for placing the GS, it is important to know exactly what the hovering region looks like. Given the constraints of avoiding tangling on neighboring buildings, ensuring that the tether is far enough from public access, and establishing a safety margin above all surrounding buildings, the hovering region of each rooftop is actually unique. For instance, if the rooftop is surrounded by shorter buildings on all sides, it will have a larger hovering region, and, hence, more mobility freedom is ensured to the tUAV. The hovering region is a function of the distances to the surrounding buildings and their relative heights. To solve the 3D placement optimization problem of a tUAV, an analytical model for the hovering region needs to be derived first.

Conclusions

In this article, we discussed the potential of tUAV for cellular coverage and capacity enhancement. The proposed setup can be thought of as a compromise that aims to replace current uUAV performance constraints resulting from limited on-board energy with mobility constraints resulting from the tether connection. We showed that tUAV systems have some promising advantages over uUAVs, despite the mobility constraints resulting from the tether. We discussed some potential use cases and applications where a tUAV-mounted BS will be of great benefit, such as capacity enhancement in urban areas, coverage enhancement in rural areas, and network densification. Finally, we discussed some open challenges and research problems that need to be well investigated to understand better the performance limitations of the proposed setup.

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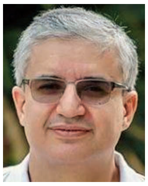

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